Analysing the hovering flight of the hummingbird using statistics of the optical flow field

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Abstract

We propose a new method to analyse and characterise the hummingbird wing dynamics using statistical measures from an optical flow field. The method starts by computing a dense optical flow, using a multi-scale spatial representation. First the pixels with larger velocities are retained as the support of the flow field, formed by the wings motion. Then, the global angular velocity is calculated as a function of the time during the hummingbird stroke. Additionally, each wing is segmented and the spatial variance of the velocity orientation is computed, providing the instants of principal stroke deformation. Finally a local measure of orientation deviation allows to localise the region of maximal torsion. Preliminary results show a compact and coherent description of the hovering flight dynamics of the hummingbird.

1 Introduction

The emulation of flying animal movements would allow micro air vehicles (MAVs) to perform complex maneuvers and to expend less energy [4]. Among these MAVs, hovering machines have the ability to perform accurate maneuvers within a limited space [4]. Efficient machine designs are nowadays considering natural mechanisms as the very base to obtain optimal movement strategies. The design of hovering MAVs can be approached by observing animals such as Hummingbirds [1]. Their maneuverability is based on their ability to turn at any direction with very little radii. However, many aspects of their flight are not fully understood yet.

Currently, there is no information about how hummingbirds perform yaw turns during hovering flight, at least about how they stay in the turn once they start this maneuver. The only available information about these turns comes from other species like gliding or flapping birds, and hovering insects [5, 13, 3, 2, 10, 6]. These animals are very different since hummingbird is entailed with simple wings that operate over a larger range of speeds [11].

Typical tools to capture information about animal motions in general, and the hummingbird dynamics in particular, are very limited and generally based on a few reference points, highlighted on the structure of the animal. Furthermore, these tools introduce artifacts that alter the natural gestures of the hummingbird movement since they need markers to be placed on the bird, and those markers can be easily occluded, like the shoulder joint for instance. Therefore the captured data do not necessarily correspond to the real dynamic patterns. Most of these kinematic methods analyse the wing as a stiff airfoil [9], but actually the wing is a flexible structure, with non uniform movement [9]. Some works have found important patterns that characterise the dynamics of the hovering hummingbird [12], highlighting the importance of doing an analysis of the whole structure and not only of some isolated reference points. However these methods explain the hummingbird movement from the aerodynamic standpoint, but not from the kinematic angle.

In this work we propose several motion patterns to describe the hummingbird wing flight, providing relevant biological information. This spatiotemporal description is based on a set of velocity vectors from a dense optical flow. Three principal patterns are computed: (1) the global angular velocity of the hummingbird, (2) the spatial variance of the orientations in the velocity field for each wing and (3) a distribution map of the local variation of the orientations within the wing. These dynamic patterns allow to follow the wing and determine its principal moment of deformation, and also the principal torsion regions, facilitating an independent analysis. This paper is organised as follows: Section 2 introduces the proposed method, section 3 demonstrates the effectiveness of the method. The last section concludes with a discussion and possible future works.

2 Materials and Methods

Our purpose is to analyse the Hummingbird dynamics as a whole, using a velocity vector field, estimated from a multiscale approach (Local Jet). This dense optical flow approach provides a comprehensive motion description by estimating the instantaneous displacement of each pixel between consecutive frames. Once obtained the representative motion vector field, three dynamic patterns are computed, for each time step: global angular velocity, global spatial variance orientation and a map of local deformations (deviation of the local orientation w.r.t the spatial average orientation for each wing). These patterns allows to understand important features of the hummingbird flight like the wing rotation and deformation.

2.1 Optical Flow Computation

The whole method starts by computing a dense optical flow using the method of the nearest neighbour in a similarity based feature space [8], so that every point of the image space (pixel) is associated to a unique position in the feature space, a position which is related to the visual appearance of the pixel. This information is obtained here using the local jets [7], an approximation of the image spatial structure provided by derivatives at different orders and scales: $f_{ij}^{\sigma} = f * \frac{\partial^{i+j} G_{\sigma}}{\partial x_1^i \partial x_2^j}$, where G_{σ} is the 2d Gaussian function with standard deviation σ. The feature vector is then given by the collection $\left\{f_{ij}^{\sigma}; i+j \leq r, \sigma \in S\right\}$, where r is the derivation order and $S = \{\sigma_1, \ldots \sigma_q\}$ the selected scales. Then, for each frame t and every pixel $\mathbf{x}$, the apparent velocity vector $\mathbf{V}_t(\mathbf{x})$ is estimated by searching the pixel associated to the nearest neighbour in the space of local jet vectors calculated at frame $t-1$. The interest of this method is to provide a dense optical flow field without explicit spatial regularization, and an implicit multi-scale estimation by using a descriptor of moderate dimension for which the Euclidean distance is naturally related to visual similarity.

2.2 Hummingbird dynamic patterns

From the dense optical flow, it is possible to compute several patterns to describe and detect particular instants or positions of the hovering flight. All the proposed descriptors are functions of time t, some of them are global, i.e. a scalar function of f some are local, i.e. a temporal sequence of map indexed by t and function of position $\mathbf{x}$.

2.2.1 Angular velocity

A global description of the hummingbird flight is obtained by computing the mean angular velocity. For a non-zero flow vector $\mathbf{V}$, let $\phi(\mathbf{V})$ denote its orientation, we compute the spatial average orientation $\overline{\phi(\mathbf{V})_t}$ at each time t. Under the assumption that the rotation axis is parallel to the optical axis of the camera and that the angular velocity does not change much spatially, the rate of change of angular displacement is then computed as $\Omega_t = \frac{d\overline{\phi(\mathbf{V})_t}}{dt}$. This important pattern describes the turn flight angle, and highlights the principal phases of relaxation and effort during the flight.

2.2.2 Local and global deformation

Taking advantage of the density of the optical flow, each wing is segmented by finding the two largest connected regions of velocity vectors. Then the isolated flow regions are annexed to the closer big region according to the Euclidean distance. Then for each time step t, for each wing, we calculate O_t^l (resp O_t^r), the average orientation of all the non-zero flow vector in the left (resp. right) wing.

A deformation map is obtained by the squared deviation of each non-zero flow vector w.r.t the average orientation in each frame:

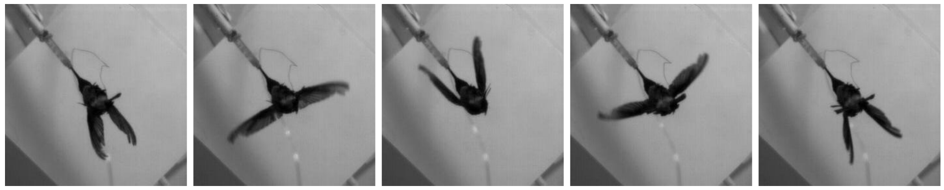
$$Q_t^l(\mathbf{x}) = ||\phi(\mathbf{V}_t(\mathbf{x})) - O_t^l||^2$$

and $Q_t^r(\mathbf{x})$ is defined the same way for the right wing. This analysis provides a stress map of the wing, highlighting the forces shearing the wing.

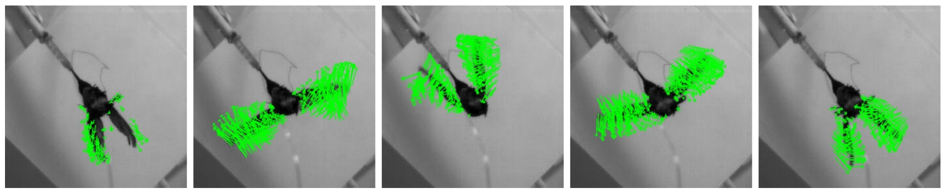
Then, for each wing, a global deformation measure W_t^l and W_t^r are obtained from the spatial orientation variance, which is simply the spatial average of the deviation map $Q_t^l(\mathbf{x})$ and $Q_t^r(\mathbf{x})$ respectively. This measure allows to detect the key instant of the deformation during a flight stroke.

2.3 Dataset description

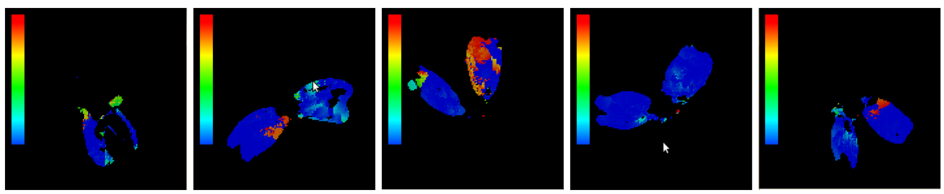
Four annas hummingbirds (*Calypte anna*) were recorded. Each hummingbird was placed inside a flight chamber that contained a wooden perch in the corner and a feeder, in which a 1 ml syringe was mounted at the end of a metallic arm ($0.22m \times 0.19m \times 0.15m$). The feeder arm was connected to a stepper motor (MDrive 23 Plus, Intelligent Motion Systems, Inc.) placed at the centre of the cage roof. This setup allowed the bird to feed from the spinning feeder while maintaining its centre of gravity in the same spot, executing a pure yaw turn. A white cardboard square was placed above the hummingbird to offer a contrasting background to the hummingbird body. The hummingbirds were trained to follow the feeder at 30 rpm. A stationary hovering flight behaviour was recorded. High speed images



(a) hummingbird flight video sequence



(b) Dense optical flow computation during the hummingbird flight. The optical flow field in each frame it is represented by a set of green arrows.



(c) Deformation map obtained from the orientation variance w.r.t to the average orientation in each frame. In this color scale the larger deformation is represented by the red color

Figure 1. Hummingbird wing motion analysis from a dense optical flow computation.

(1000 frames/s) of the hummingbird flying in the cage were recorded by a High speed camera (Fastec Imaging, Troubleshooter). A total of 40 flight cycles were considered in this study.

3 Results

A typical flow output from videos of the hummingbird flight is shown in the figure 1(b). As shown, the velocity vectors are mainly focused around the wings, but may be localized outside of them, due to the change in the multiscale structure that occur in these regions and are detected by the local jet approach. In our experiments, we used 7 scales of estimation, with $\sigma_0 = 0.3$ and $\sigma_{n+1} = 2\sigma_n$, and derivatives up to order 2, resulting in a descriptor vector of dimension 42.

Figure 2 shows Ω_t, the global angular velocity over the time computed for different versions of the same flight cycle (corresponding to the different colours). The small variations between the different samples shows a good repeatability of the measure. Between the 40 and 60 percent of the stroke, there is an interesting change of velocity, which represents two important states of relaxation and effort produced during the flight, when the wings are joining and then splitting again.

The second global measure W_t^l (resp. W_t^r) allows

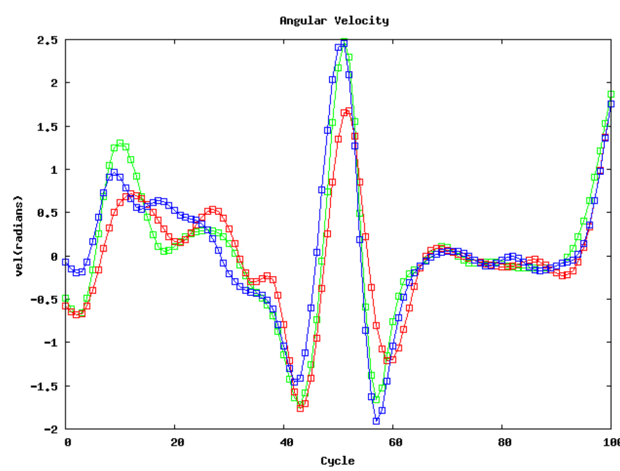


Figure 2. Variation of the angular velocity during the stroke cycle for different examples

to identify the maximum deformation instants during the stroke. Figure 3, shows some typical functions obtained on one wing during a stroke cycle. The different measures are also consistent, highlighting the principal moments of the wing deformation.

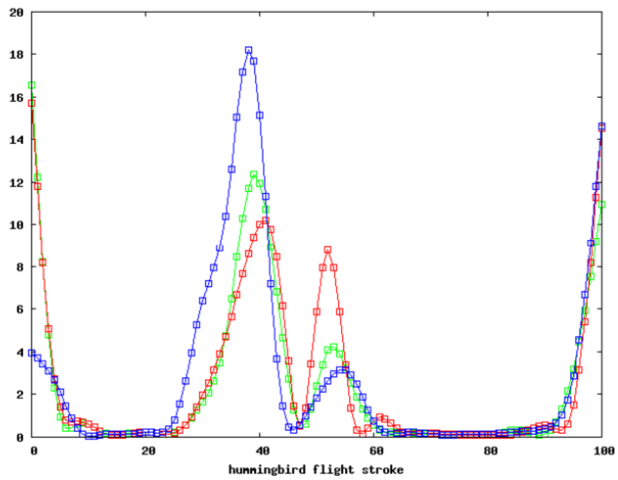


Figure 3. Wing deformation pattern in each wing during the flight.

Finally the local measure $Q_t(\mathbf{x})$ forms a saliency map as illustrated in Figure 1(c). This map was computed independently for each wing and shows the principal regions of torsion during the stroke.

The methodology herein proposed constitutes a first approximation to understand the complex dynamics of the hummingbird using statistical measures from a dense optical flow.

4 Conclusion

A novel method to analyse the dynamics of the hummingbird hovering flight was proposed. The method is based on a statistical characterisation of a dense optical flow computed on videos of hummingbird flight, without using any visual markers. Global and local dynamic wing features were computed, showing a coherent and repeatable motion description. From this kind of analyses we expect to characterise and accurately describe motion patterns free of invasive devices which alter the natural dynamic of this bird. Also from these computational tools it is possible to describe more complex structural changes of the wing during the flight, like the deformation. Finally, the proposed work is not specific to this movement and can be extended to analyse other animal motions.

References

[1] D. Altshuler and R. Dudley. The ecological and evolutionary interface of hummingbird flight physiology. *J. Exp. Biol,*, 205:2325–2336, 2002.

[2] D. R. B.-M. Warrick and D. K. P. Bird maneuvering flight: blurred bodies, clear heads. *Integrative and Comparative Biology*, 42:141–148, 2002.

[3] D. R. D.-K. P. Warrick and A. A. Biewener. Asymmetrical force production in the maneuvering flight of pigeons. *auk. The Auk*, 115:916–928, 1998.

[4] S. D. E. de Margerie, J. B. Mouret and J. Meyer. Artificial evolution of the morphology and kinematics in a flapping-wing mini uav. *Bioinspir. Biomim*, 2:65–82, 2007.

[5] T. L. Hedrick and A. A. Biewener. Low speed maneuvering flight of the rose-breasted cockatoo (eolophus roseicapillus) i. kinematic and neuromuscular control of turning. *J. Exp. Biol*, 210:1897–1911, 2007.

[6] J. W. D.-S. K. R. D. Dawson and R. Robertson. Forewing asymmetries during auditory avoidance in flying locusts. *J. Exp. Biol*, 200:2323–2335, 1997.

[7] M. V. L. Florack, B. Ter Haar Romeny and J. Koenderink. The gaussian scale-space paradigm and the multiscale local jet. *Int. J. of Computer Vision*, 18(1):61–75, 1996.

[8] A. Manzanera. Local jet feature space framework for image processing and representation. 2011.

[9] E. S. L. U. P. Wu, B. Stanford and P. Ifju. Structural dynamics and aerodynamics measurements of biologically inspired flexible flapping wings. *Bioinspiration and Biomimetics*, 6:016009, 2011.

[10] S. N. R. Fry and M. H. Dickinson. The aerodynamics of free-flight maneuvers in drosophila. *Science*, 300:495–498, 2003.

[11] D. T. B.P. D. Warrick and M. Dickinson. The aerodynamics of hummingbird flight. *American Institute of Aeronautics and Astronautics*, 2007.

[12] D. R. T.B. W. Warrick and D. R. Powers. Aerodynamics of the hovering hummingbird. *Nature*, 435:1094–1097, 2005.

[13] T. L. U.-J. R. Hedrick and A. A. Biewener. Low speed maneuvering flight of the rose-breasted cockatoo (eolophus roseicapillus). ii. inertial and aerodynamic reorientation. *J. Exp. Biol*, 210:1912–1924, 2007.

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